Assessing the Limitations and Qualification Criteria of CFD-Based Numerical Wave Tanks using High-Performance Computing (HPC)

Milad Abdollahpour, University of Florence, m.abdolahpour@yahoo.com
Federico Domenichini, University of Florence, federico.domenichini@unifi.it
Lorenzo Cappietti, University of Florence, lorenzo.cappietti@unifi.it

ABSTRACT

A Numerical Wave Tank (NWT) refers to a class of numerical simulators used in the field of ocean engineering to model nonlinear free surface waves, hydrodynamic forces, and the motions of floating bodies. In comparison with laboratory wave tanks, NWTs are more flexible and cost-effective in tank layout adjustment and data analysis. Numerical wave tanks, supported by CFD and High-Performance Computing (HPC), have emerged as strong tools for studying wave dynamics and their practical applications. These virtual laboratories enable comprehensive wave analysis and marine structure design. However, realizing their potential necessitates a detailed understanding of their limitations and the establishment of rigorous qualification criteria. The field of Computational Fluid Dynamics (CFD) applied to Numerical Wave Tanks (NWTs) has significant progress, driven by the demand for precision and computational efficiency in simulating complex wave phenomena.

This research delves into the intricacies of assessing the reliability and accuracy of CFD-based numerical wave tanks, particularly in the context of HPC-driven simulations. This project focuses on the development of a Numerical Wave Tank (NWT) for studying wave-structure interaction. By utilizing high-performance computing (HPC) and advanced numerical methods, the aim is to accurately simulate complex dynamics. To achieve this goal, a comprehensive review of open-access computational fluid dynamics (CFD) tools suitable for HPC architectures has been conducted. By better understanding wave-structure interactions, it becomes possible to optimize the design and performance of these structures and improve the efficiency of wave-energy converters, thereby driving progress in renewable energy generation from waves.

In this study, numerical simulations were performed using OpenFOAM. Within the CFD-based NWT domain, OpenFOAM has gained prominence as an open-source toolbox well-suited for high-fidelity simulations. It excels in simulating fluid flow, including the complexities of free-surface flows and wave propagation. OpenFOAM's extensive capabilities, including its vast array of solvers and utilities, make it an invaluable asset for tackling complex NWT simulations.

OpenFOAM's capabilities extend to parallel computing, which is particularly advantageous in high-performance computing (HPC) environments. The software's computational framework centers around domain decomposition, a parallel computing approach. This strategy involves partitioning the computational domain and its mesh into discrete sub-domains, which are allocated to individual processors for concurrent computation.

In this study, to simulate waves, we considered two-phase fluids, water, and air, in surface wave simulations. These fluids were assumed to be incompressible, at a constant temperature, and incapable of mixing with the Volume-of-Fluid (VOF) method. We considered the fluid motion due to a moving vertical wall for a wavemaker of the piston type, as depicted in Figure 1.

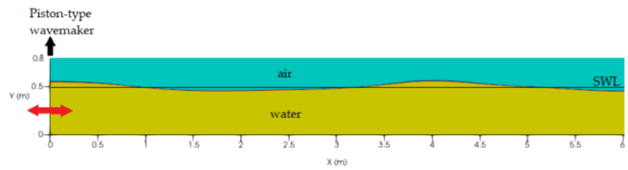

Figure 1 - Generation regular wave with piston-type wave maker

As a result, the integration of HPC into CFD-based Numerical Wave Tanks plays a crucial role in enhancing simulation precision. NWT simulations involve intricate challenges, including turbulence modeling intricacies, grid resolution, and boundary condition sensitivity, all of which influence result accuracy. HPC leverages advanced techniques to address these limitations. It enables finer grid resolutions and reduces computational time thereby providing a path to exceedingly detailed simulations. The interplay between model complexity and computational resource allocation becomes more manageable with HPC, which allows researchers to achieve precision efficiency. The resolution and fidelity of NWT simulations depend on HPC's ability to handle high computational demands.

In conclusion, the combination of CFD-based numerical wave tanks and High-Performance Computing (HPC), especially when integrated within the OpenFOAM framework, represents a groundbreaking platform for conducting in-depth analyses of wave dynamics and exploring their practical implications. The precision, efficiency, and adaptability provided by this combination are crucial for enhancing the accuracy and applicability of numerical wave tank simulations in the fields of coastal and ocean engineering.

The development of Numerical Wave Tanks (NWTs) offers a cost-effective approach for experimentation, analysis, and optimization in the research and development (R&D) of Wave Energy Converters (WEC). Utilizing high-performance computing and advanced numerical methods allows us to gain a profound understanding of flow phenomena and their impacts on wave-energy systems.

ACKNOWLEDGMENTS

The University of Florence acknowledges the contribution of the National Recovery and Resilience Plan, Mission 4 Component 2 - Investment 1.4 - NATIONAL CENTER FOR HPC, BIG DATA AND QUANTUM COMPUTING, funded by the EU - NextGenerationEU - (CUP B83C22002830001).